Purdue University
Purdue e-Pubs

ASEE IL-IN Section Conference | 2019 ASEE IL-IN Section Conference

Using definitions of concepts in introductory physics courses for scientists and engineers

Christos Deligkaris
University of Southern Indiana, dr.deligkaris@usi.edu

Using Definitions of Concepts in Introductory Physics Courses for Scientists and Engineers

Abstract

Introductory physics courses are to some extent the pillars of the more advanced and specialized engineering courses. In traditional introductory physics instruction at high schools and universities, fundamental concept definitions (e.g. acceleration is the rate of change of velocity with respect to time) are de-emphasized and a number of case-specific equations (e.g. the traditional constant-acceleration kinematic equations) are used. Emphasizing fundamental concept definitions in physics education provides significant advantages, including consistency of concept-interpretation in all representations and the ability to make general inferences about specific cases among others. Breakthroughs in engineering, such as new materials, new technologies, or dramatic cost reductions, sometimes rely on use of first principles. In this paper, advantages and disadvantages of emphasizing concept definitions in multiple representations in introductory physics, based on education research and my own teaching experiences, will be discussed. Assessment data are also presented which show that using the definitions of concepts in all aspects of the introductory physics courses (lecture, homework etc.) allows students to achieve high learning gains.

KEYWORDS: introductory physics, case-specific, definition

Introduction

Physicists often take pride in how a small number of concepts and relationships between concepts (principles) can explain and predict a vast number of physical phenomena. Traditional introductory physics textbooks for scientists and engineers emphasize predominantly case-specific equations and de-emphasize the small number of fundamental physics concept definitions, especially in the algebraic representation (mathematical equations). Case-specific equations are valid only if specific conditions are met.

For example, the algebraic equations very often emphasized in traditional kinematics (study of motion) are the following:

$$\vec{r} = \vec{r}_i + \vec{v}_i \Delta t + \frac{1}{2}\vec{a}(\Delta t)^2 \quad (1)$$

$$\vec{v} = \vec{v}_i + \vec{a}\Delta t \quad (2)$$

$$v_j^2 = v_{j,i}^2 + 2a_j \Delta r_j \quad (3)$$

where j is x, y, or z; i indicates an initial quantity; $\vec{r}$ is the position vector; $\vec{v}$ is the velocity vector; and $\vec{a}$ is the acceleration vector. Equations 1-3 are valid only if acceleration is constant. In contrast, the definitions of velocity and acceleration (Equations 4, 5) are much less often used.

$$\vec{v} = \frac{\Delta\vec{r}}{\Delta t} \tag{4}$$

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t} \tag{5}$$

Typically, the definitions of physics concepts (such as Equations 4, 5) are used to derive case-specific equations (such as Equations 1-3) in introductory physics textbooks; however, they are not used extensively in problem-solving. Other examples of case-specific equations are found in rotational motion, work, and electric fields.

Physicists need a precise definition of physics concepts for the unambiguous application of concepts in the natural sciences. Percy Bridgman (Nobel Prize in physics, 1946) discussed the importance of physical operations in defining physics concepts [6] and Arnold Arons, a leader in physics education, discussed the importance of emphasizing operational concept definitions in physics education [4]. Operational (or procedural) definitions of scientific concepts provide a method that one has to follow in order to properly apply the concept to a specific situation [16].

In addition to their definition, physicists also need concept-representations. Physics concepts can be represented as arrows (pictorial representation), graphs (graphical representation), or mathematical equations (algebraic representation), and sometimes multiple representations are used in physics education.

The innovative *RealTime Physics labs* [18] and *Tutorials in Introductory Physics* [13] emphasize the operational definitions of concepts in graphical and pictorial representations and have been shown to help students learn more [19],[14]. Why, then, do introductory physics textbooks emphasize case-specific equations in the algebraic representation? In this paper, we discuss an example from kinematics, together with assessment data and advantages/disadvantages of emphasizing definitions of concepts.

Example

I will illustrate the approach with a simple example (based on an example found elsewhere[11]) that highlights the use of the definitions of velocity and acceleration in the pictorial, graphical, and algebraic representations.

Problem: A car is moving at 10m/s when an obstacle suddenly appears on the street. The driver hits the breaks and the car comes to rest in 2s. How far did the car travel while braking to a stop?

Solution: Step 1. Let's assume that the car has a constant acceleration a_x during this motion and that the direction of the initial velocity is the direction of $+\hat{x}$.

$$a_x = -k$$

where k is a positive number. Using the definitions of change in velocity and acceleration (Equations 4 and 5), we can plot the motion diagram of the car (Figure 1, pictorial representation).

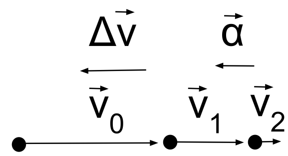

Figure 1: The motion diagram of the car modelled as a point particle.

Acceleration represented as a graph:

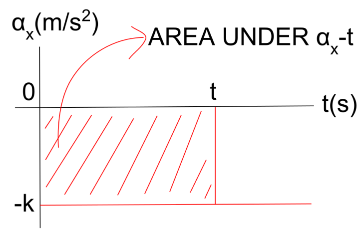

Figure 2: The graph of a_x as a function of time. Note that by obtaining the change in velocity by calculating the area under this graph in this graphical representation we are consistent with our work in Step 4, where we obtain the change in velocity in the algebraic representation.

Step 2. Since acceleration is the slope of the velocity-time graph (Equation 4) and we know the initial velocity, we can also construct the v_x-t graph:

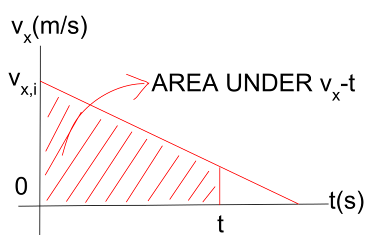

Figure 3: The graph of v_x as a function of time. Note that by obtaining the change in position by calculating the area under this graph in this graphical representation we are consistent with our work in Step 5, where we obtain the change in position in the algebraic representation.

Step 3. Similarly, since velocity is the slope of position-time graph (Equation 4), and assuming that $x = 0$ when $t = 0$, we can also obtain the $x - t$ graph:

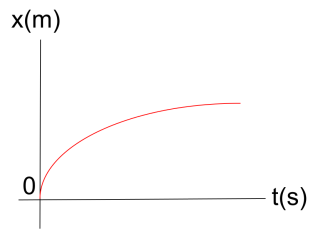

Figure 4: The graph of x as a function of time.

Step 4. Employing the definition:

$$a_x = dv_x/dt \Rightarrow \Delta v_x = \int_{t_i}^{t_f} a_x dt$$

In the graphical representation, this integral is the area under the a_x curve. To find Δv_x, we could either integrate analytically:

$$\Delta v_x = \int_0^t a_x dt' = \int_0^t -k dt' = -k(t-0) = -kt$$

or use graphs. An explicit calculation of the area under the a_x versus t graph also gives $-k(t-0)$ or $-kt$; thus,

$$\begin{aligned} \Delta v_x &= v_x - v_{x,i} = -kt \\ v_x &= v_{x,i} - kt \\ v_x &= 10 - kt \end{aligned}$$

Since $v_x = 0$ when $t = 2$s, we get $k = 5$. So, $v_x = 10 - 5t$. Check: our algebraic representation of velocity agrees with the graphical representation, since both have a negative slope and when $t = 0$ velocity is 10m/s.

Step 5. Now to find the equation for position as a function of time, from Equation 4 we get:

$$v_x = dx/dt \Rightarrow \Delta x = \int_{t_i}^{t_f} v_x dt$$

Working from the graphical representation, we can evaluate the integral as the area under the $v_x - t$ graph, which gives:

$$(1/2)(v_{x,i} + v_x)t = (1/2)(20 - 5t)t = 10t - 2.5t^2$$

Equivalently, integrating analytically gives:

$$\int_0^t v_x dt' = \int_0^t (10 - 5t')dt' = 10t - 2.5t^2$$

Since

$$\Delta x = \int_0^t v_x dt'$$
$$\Delta x = 10t - 2.5t^2$$

The displacement from $t = 0$ to $t = 2$ s is then $\Delta x = 20 - 10 = 10$m. The algebraic equation for position (note that $x_i = 0$) is

$$x - x_i = x = 10t - 2.5t^2$$

Check: our algebraic representation of position agrees with the graphical representation since they both describe a parabola.

Assessment

I have been emphasizing the definitions of concepts in my introductory physics courses for the last six years. The example from kinematics shown above demonstrates the expectations I have from my introductory physics students for how to approach problem solving. The definitions of concepts are to be used to solve kinematics problems. The first thing I wanted to evaluate was whether such an approach prevented students from making significant conceptual learning gains. I used assessment instruments, developed by research in physics education, to assess student learning. My students were able to score (post-test) 79% ($N = 26$) - 84% ($N = 23$) in the validated Test of Understanding Graphs - Kinematics (TUG-K) instrument [5]. Students have also achieved an average normalized learning gain of 47% ($N = 22$) - 52% ($N = 26$) in the validated Force Concept Inventory (FCI) instrument, which assesses student learning of understanding Newtonian mechanics [10]. These learning gains are significantly larger than the gains achieved in traditional introductory physics courses (about 15-20%). The data presented here are from an introductory physics class at a small (about 1300 students) private liberal arts college. The students were science majors. This evidence suggests that emphasizing the definitions of physics concepts in introductory physics does not prevent students from making significant learning gains. Future work will include student interviews in order to collect evidence for the benefits of emphasizing the definitions of concepts in introductory physics.

Advantages

One advantage in emphasizing concept definitions in all representations is the consistency achieved in the interpretation of concepts in the different representations. As an example from kinematics, the definition of acceleration can be used in both the algebraic and pictorial representations in order to determine the direction of acceleration. This advantage can be important in introductory physics courses where multiple representations of concepts are extensively used and students have to translate information from one representation to another. The ability to use multiple representations is highly valued in physics, and it may even be a necessary condition for expertise in physics [12]. Also, if students use the area under a pressure-volume graph to calculate the work done by an ideal gas in an engineering or chemistry course and the area under a force-position graph (as opposed to a case-specific equation) to calculate work done by a force in a general physics course, it may be easier for them to understand the connection between the two.

By relying on the definitions of concepts in introductory physics, we have increased consistency within the undergraduate physics curriculum because both introductory and upper-level students could be using the same algebraic techniques to analytically solve problems (some engineering students do take upper level physics courses). Upper-level students working on problems with air resistance, for example, could use the (graphical or analytical) integration techniques learned in introductory physics to determine the equations that describe the motion.

Arons argued that including problems that involve only constant acceleration implants the misconception that all calculations are to be made with the formulas applying to the constant special cases and that it is impossible to deal with cases of continuous change [3]. Probably, similar misconceptions may exist by including problems that involve only constant forces, electric fields, etc. Using the definitions of concepts could make it easier to include problems that involve non-constant physics concepts, which could in turn help alleviate this misconception in introductory physics.

Definitions can provide both average and instantaneous quantities of concepts, and they are always valid. With such generally applicable definitions, we can make general inferences. As an example from kinematics, to determine whether acceleration is zero when the velocity of the particle is zero, we could use the general definition of acceleration (for more details on this example please see reference [15]). Using only the definitions could also help clarify that i) it is the *change* of position and velocity that determine velocity and acceleration respectively, and ii) from velocity and acceleration we can only get the *changes* in position and velocity respectively. As an example from electrostatics, using the area under an electric field-position graph may help clarify that we can only get *changes* of potential from the the electric field.

With an approach based on concept-definitions, students will have to start from fundamental knowledge (for example, the definition of velocity), make assumptions about the physical phenomenon (for example, constant velocity), and, finally, combine the two to build the physics model. Thus, by emphasizing the definitions of concepts, we provide an additional argument to our students to make their assumptions explicit. Starting from fundamental principles also helps our engineering students understand the thinking process that may be sometimes needed for breakthroughs in technology [1].

There are several ways to define a concept [16]. As mentioned in the introduction, operational (or procedural) definitions of scientific concepts provide a method that one has to follow in order to properly apply the concept to a specific situation [16]. Within the approach “idea first, name afterwards”, Arons argued that using operational definitions increases student understanding of difficult physics concepts [2]. Thus, when emphasizing definitions of physics concepts, it is important to provide to our students the process they need in order to apply these concepts.

Emphasizing general (operational) definitions of concepts does not imply that physics students should not be proficient with case-specific equations (such as Equations 1-3) and know when and how to use them; however, students will probably benefit if they are exposed to case-specific equations after mastering the application of concept-definitions. This is because students need to be able to use the fundamental definitions in order to resolve inconsistencies that arise in their case-specific knowledge [16]. Previous studies provide examples of such difficulties with the concepts of velocity and acceleration due in part to students having compiled case-specific knowledge without the general knowledge background from which special cases can be inferred [17]. In addition, the efficiency that case-specific equations allow is an asset primarily for advanced problem-solvers, due to the reduced demand on finite mental resources [16]. Thus, we need to first emphasize the operational definitions of concepts and let the students master those before introducing case-specific knowledge. Reif has also argued that the students should be the ones that compile the case-specific knowledge, using the procedural specifications they just mastered [16]. Some resistance from students is to be expected, since students sometimes do not value acquiring coherent knowledge and prefer focusing on facts and formulas [9].

An approach in introductory physics that emphasizes the definitions of concepts in all representations is also consistent with computational iterative processes, as implemented, for example, in the Matter & Interactions [7],[8] curriculum: the former utilizes analytical integration whereas the latter utilizes numerical integration.

Disadvantages

Emphasizing definitions of concepts comes with disadvantages: most significantly, using the definitions of concepts in the algebraic representation can sometimes be less time-efficient than other approaches during both learning and teaching. For example, when acceleration is constant, the traditional kinematic equations will be more efficient than a definition-only approach. We need to keep in mind, however, that while efficiency is important, is not the most important goal in teaching physics. Just because students can plug-in a few numbers in an equation and rapidly get the numerical result that solves the problem, this does not necessarily mean that the students have a functional understanding of the concepts we want them to understand. Since introductory physics is taught by experts, who are in general concerned about efficiency, it perhaps should not come as a surprise that the curriculum taught for decades emphasizes case-specific knowledge.

Emphasizing concept definitions in calculus-based introductory physics courses means that derivatives and integrals would be used extensively. The use of multiple representations on the other hand gives our students the freedom to choose whether to integrate graphically or algebraically, depending on their comfort level with those two representations. As Arons argued on kinematics [2], the curriculum may become more meaningful, and perhaps easier, if we allow our students to see the relevant motion concepts as areas under graphs, which, I add, they can calculate in the representation they prefer (graphical or algebraic via integrals).

For algebra-based physics courses, which some engineering majors, such as industrial supervision or advanced manufacturing take, the emphasis could be on the application of concept definitions in the pictorial and graphical representations, with students finding slopes of graphs and areas under graphs. Given that the *Tutorials in Introductory Physics* [13] and *RealTime Physics labs* [18] emphasize the pictorial and graphical representations and have contributed in effective student-learning [19],[14], minimizing the usage of case-specific algebraic equations in algebra-based physics courses may not prevent students from strong learning gains.

Conclusions

In introductory physics instruction, case-specific algebraic equations are often used, presumably due to their efficiency. Emphasizing fundamental concept definitions, however, provides other significant advantages that should not be overlooked. Physics education research could help determine the extent of the need for case-specific equations in introductory physics.

References

[1] The first principles method explained by Elon Musk. https://youtu.be/NV3sBlRgzTI.

[2] A.B. Arons. Student patterns of thinking and reasoning. *Phys. Teach.*, 22(1):21–26, 1984. doi: http://dx.doi.org/10.1119/1.2341444. URL http://scitation.aip.org/content/aapt/journal/tpt/22/1/10.1119/1.2341444.

[3] A.B. Arons. Student patterns of thinking and reasoning. *Phys. Teach.*, 22(2):88–93, 1984. doi: http://dx.doi.org/10.1119/1.2341474. URL http://scitation.aip.org/content/aapt/journal/tpt/22/2/10.1119/1.2341474.

[4] A.B. Arons. *Teaching Introductory Physics*. Wiley, 1996.

[5] R.J. Beichner. Testing student interpretation of kinematics graphs. *Am. J. Phys.*, 62(8):750–762, 1994. doi: http://dx.doi.org/10.1119/1.17449. URL http://scitation.aip.org/content/aapt/journal/ajp/62/8/10.1119/1.17449.

[6] P. Bridgman. *The logic of modern physics*. The Macmillan Company, 1927.

[7] R. W. Chabay and B. A. Sherwood. *Matter & Interactions: Modern Mechanics*, volume 1. John Wiley & Sons, 2011.

[8] R. W. Chabay and B. A. Sherwood. *Matter & Interactions: Electric and Magnetic Interactions*, volume 2. John Wiley & Sons, 2011.

[9] D. Hammer. Epistemological beliefs in introductory physics. *Cognition Instruct.*, 12(2):151–183, 1994. doi: 10.1207/s1532690xci1202_4. URL http://dx.doi.org/10.1207/s1532690xci1202_4.

[10] David Hestenes, Malcolm Wells, and Gregg Swackhamer. Force concept inventory. *Phys. Teach.*, 30(3):141–158, 1992. doi: http://dx.doi.org/10.1119/1.2343497. URL http://scitation.aip.org/content/aapt/journal/tpt/30/3/10.1119/1.2343497.

[11] R. D. Knight, B. Jones, and S. Field. *College Physics: a strategic approach*. Pearson Ecucation Inc., 2010.

[12] L. McDermott. A view from physics. In M. Gardner, J.G. Greeno, F. Reif, A.H. Schoenfeld, and A.A. diSessa, editors, *Toward a scientific practice of science education*. Routledge, 1990.

[13] L. C. McDermott, P. S. Shaffer, and the Physics Education Group. *Tutorials in Introductory Physics*. Prentice Hall, Inc, 2002.

[14] S. J. Pollock. Longitudinal study of student conceptual understanding in electricity and magnetism. *Phys. Rev. ST Phys. Educ. Res.*, 5:020110, Dec 2009. doi: 10.1103/PhysRevSTPER.5.020110. URL http://link.aps.org/doi/10.1103/PhysRevSTPER.5.020110.

[15] F. Reif. Interpretation of scientific or mathematical concepts: Cognitive issues and instructional implications. *Cognitive Sci.*, 11(4):395–416, 1987. ISSN 1551-6709. doi: 10.1207/s15516709cog1104_1. URL http://dx.doi.org/10.1207/s15516709cog1104_1.

[16] F. Reif. *Applying cognitive science to education: thinking and learning in scientific and other complex domains*. MIT press, 2008.

[17] F. Reif and S. Allen. Cognition for interpreting scientific concepts: A study of acceleration. *Cognition and Instruction*, 9(1):1–44, 1992. doi: 10.1207/s1532690xci0901_1. URL http://dx.doi.org/10.1207/s1532690xci0901_1.

[18] D. R. Sokoloff, R. K. Thornton, and P. W. Laws. *RealTime Physics: Active Learning Laboratories*. John Wiley & Sons, Inc, 2012.

[19] R.K. Thornton and D.R. Sokoloff. Assessing student learning of Newton's laws: The force and motion conceptual evaluation and the evaluation of active learning laboratory and lecture curricula. *Am. J. Phys.*, 66(4): 338–352, 1998. doi: http://dx.doi.org/10.1119/1.18863. URL http://scitation.aip.org/content/aapt/journal/ajp/66/4/10.1119/1.18863.